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A RESERVOIR VERSUS ADDITIONAL PUMPAGE CAPACITY FOR SUPPLYING PEAK DEMANDS[1]

By L. A. Quayle[2]

In the planning of a new waterworks project of comparatively large size, or the enlarging of one that is in service, it is necessary to determine how much of the hourly, daily, or monthly peak demands shall be taken by one or more equalizing or distributing reservoirs and how much by pumping engines in addition to those required to supply the average quantity of water consumed over a given period. It is assumed that the topography of the area to be supplied is such that reservoir sites are available.

In villages or cities of comparatively small size, the capacities of stand pipes or reservoirs are largely determined by the fire protection requirements, rather than the considerations discussed herein. As the size of the city increases the relative capacity of the reservoir required for fire protection becomes less and less, until in a city the size of Cleveland the quantity of water used for a large fire is such a small part of the total daily consumption, that it has no appreciable effect on the hourly rate of pumpage or the daily quantity pumped.

[1] Presented at the Cleveland Convention, June 7, 1921. Discussion of this paper is desired and should be sent to the Editor.

[2] Chief Mechanical Engineer, Cleveland Water Department, Cleveland, Ohio.

In this discussion we are referring only to the equalizing or distributing types of reservoirs. The equalizing reservoir being one that is connected to the pumping station through the distribution system, and the distributing reservoir being one which receives all the water from the pumping station before it flows by gravity into the distribution system. Impounding or storage reservoirs, except where they are elevated sufficiently above a city to supply the water by gravity, do not act as equalizing reservoirs for the distribution system and are therefore not of interest in so far as this particular problem is concerned.

We are assuming throughout this discussion that the equalizing or distributing reservoir is elevated sufficiently above the highest buildings being supplied and that the distribution mains are of sufficient size, to allow the water level in the reservoir to fluctuate over a wide range without appreciably affecting the distribution pressure.

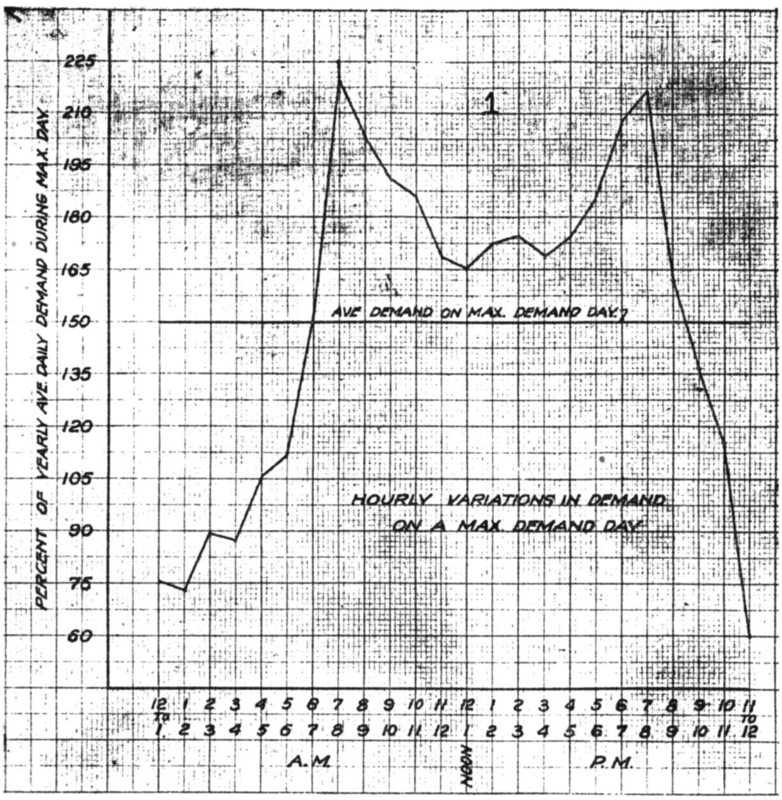
While no two cities have exactly the same ratio of hourly, daily, and monthly demands to meet, or have just the same ratio of intake, pumping station and filter plant cost, to reservoir cost, that hold good for Cleveland, we believe that our conditions are sufficiently representative of those which obtain in a large number of cities, that the analysis we have made of additional pumpage capacity versus reservoir capacity will be useful as a guide in the design of waterworks systems when the particular local conditions of the waterworks being planned are given due consideration.

In order to determine for what variation in demand for water a reservoir should be planned, we have studied the department's pumpage and water consumption records back to the year of 1910, and we have assumed that the maximum variation in demand a reservoir will be required to meet, corresponds to the maximum variation found on the maximum day, week, or month of the maximum year during the ten year period.

In order to simplify the computations, we have based our pumpage demand and cost curves on an average yearly water consumption of 100,000,000 gallons per day which is referred to as 100 per cent capacity on the various curves.

Curve 1 shows graphically the hourly variation in demand on a maximum demand day. The quantity of water pumped on a maximum demand day would be 150,000,000 gallons, and the rate of demand for the period of an hour would vary from 220,000,000 gallons per day from 7:00 to 8:00 a.m. to 60,000,000 gallons per day

from 11:00 p.m. to midnight. The maximum momentary rate of pumpage would be approximately 225,000,000 gallons per day for a few minutes between 7:00 and 8:00 a.m. If a pumping station furnished water at a uniform rate of 150,000,000 gallons per day, a reservoir of 20,600,000 gallons capacity would take care of all the hourly and momentary fluctuations shown on the curve. If



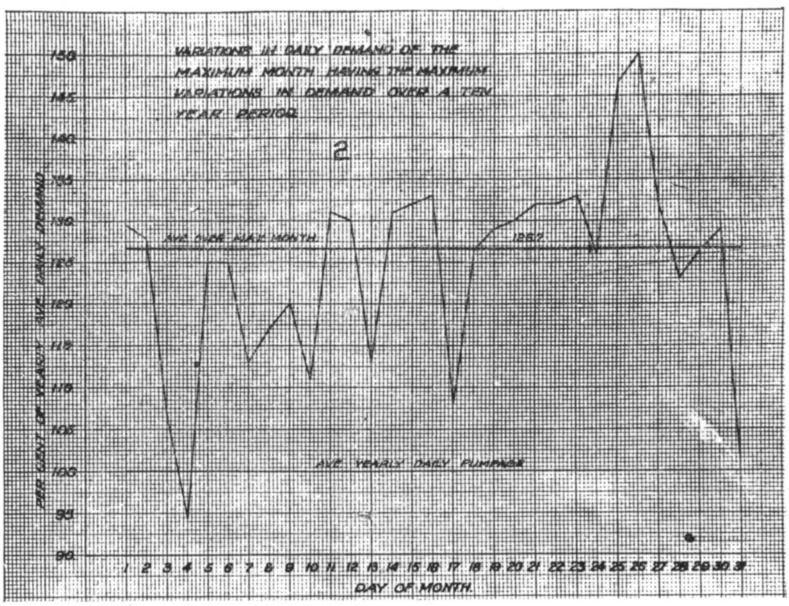
Curve 1

no reservoir were used a pumpage capacity of 225,000,000 gallons per day would be required.

Curve 2 shows the variation in daily demand of the month having the maximum variation in the maximum year of the ten year period. The average pumpage for the maximum month would be 126,700,000 gallons per day. The maximum sustained pumpage above the average monthly pumpage would be for the 8-day period

from the 20th to the 27th inclusive, which would average 135,200,000 gallons per day. A reservoir large enough to take care of the 8-day sustained demand and the two days of highest pumpage, the 25th and 26th, on which days the demand was 147,000,000 and 150,000,000 gallons per day respectively, would more than take care of all other variations in demand during that month, or any other month of the ten year period.

Curve 3 shows graphically the monthly variation in pumpage in the year having the greatest variation over the ten year period.



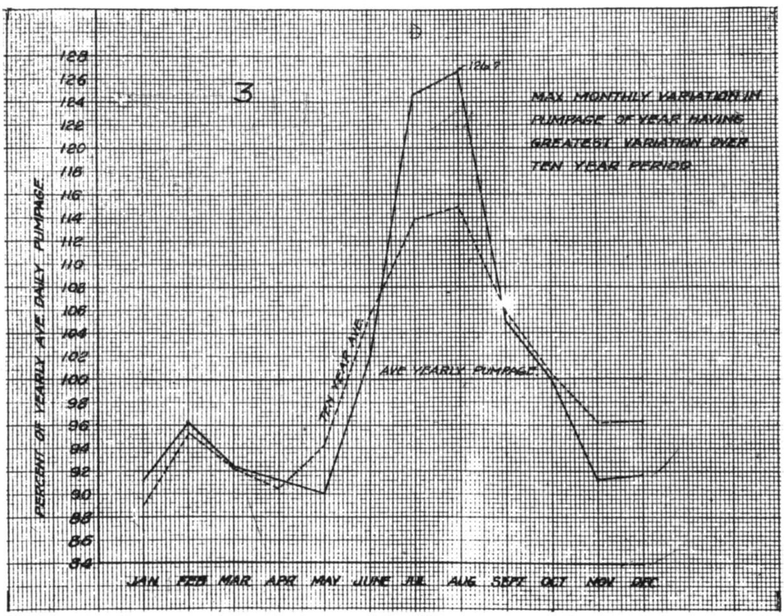
CURVE 2

You will note that the average pumpage of the maximum month would be 126,700,000 gallons per day as was also shown on curve 2. If the pumping station should work at a uniform rate of 100,000,000 gallons per day throughout the entire year, a reservoir having a capacity of 1,800,000,000 gallons would be required to take care of all variations.

Curve 4 shows graphically the various capacities of the reservoir required to take care of all variations in demand throughout the year with pumping stations of varying capacity, it being assumed as be-

fore stated, that 100 per cent demand corresponds to an average yearly demand of 100,000,000 gallons per day.

A study of curve 1 showed that a 20,600,000 gallon reservoir would take care of hourly fluctuations on a maximum day of 150,000,000 gallons per day demand, with a pumpage of 150,000,000 gallons. With a station of larger capacity the size of reservoir decreases as shown on the curve. With a pumping station of less than 150,000,000 gallons per day, the two days of 147,000,000 and

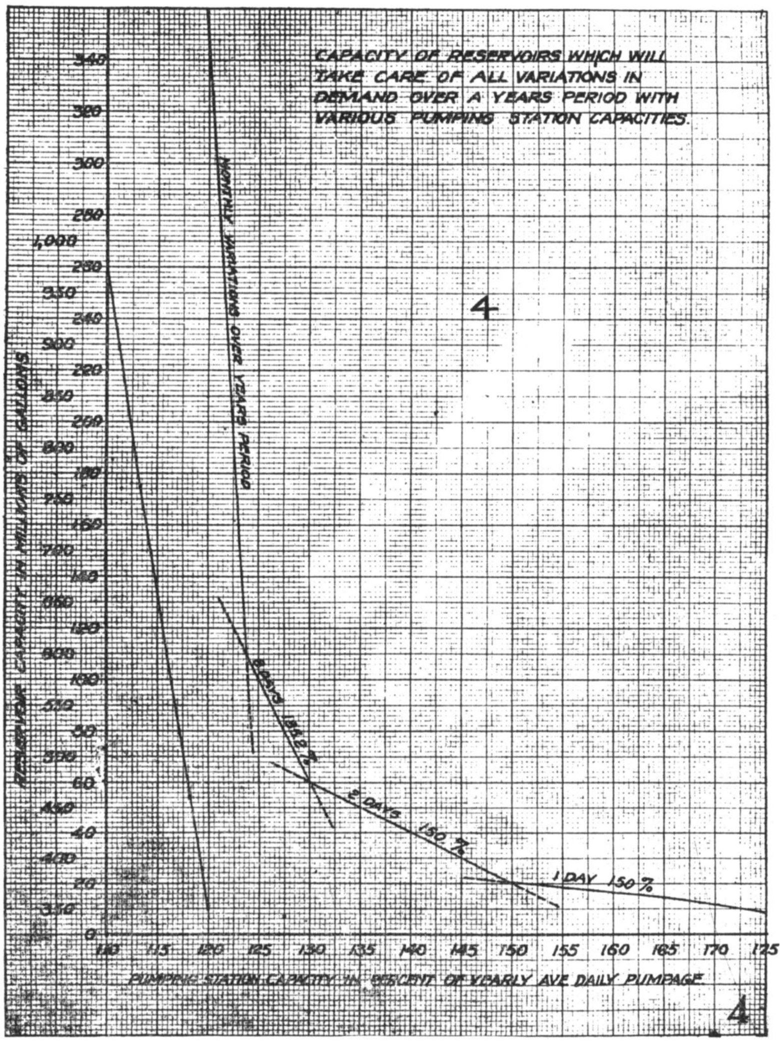


Curve 3

150,000,000 gallons per day (to simplify, say two days of 150,000,000 gallons per day demand) become the factor which determines the size of the reservoir up to the point where the 8 days of 135,200,000 gallons per day pumpage require greater reservoir capacity, which corresponds to a station of 130,000,000 gallons per day capacity.

The 8-day demand line crosses the line showing the reservoir capacity necessary to take care of the monthly fluctuations over a year's period, at a pumping station capacity of approximately 124,000,000 gallons per day.

By combining these lines into one curve we can determine from the curve the size of the reservoir required to take care of any de-



CURVE 4

mands which will be made upon it over a year's period, with different capacities of pumping stations supplying the average demand.

Having determined from the curve the combination of sizes of pumping station and reservoir required to take care of all fluctuations in demand, we must next find out what the first cost of the various combinations is, in order to determine the most economical combination to construct, in so far as first cost is concerned.

The costs of the cribs, tunnels, pumping stations, reservoirs, etc., used are based on the average cost of Kirtland and Division tunnel systems and pumping stations, Fairmount, Kinsman and Warrensville reservoirs, and Division Avenue filtration plant. All capital operation and maintenance charges are based on pre-war costs. Since we are interested primarily in the ratio of the cost of one type of construction to another and not in the absolute cost, we believe the use of the comparatively stable pre-war prices is preferable to trying to change these costs to the present unstable basis.

We have tabulated below the approximate costs of our various waterworks projects, the average cost per million gallons of capacity for each, and the assumed life of the property upon which we based the annual fixed charges.

Cost of cribs, tunnels, aqueducts and screen wells

	KIRTLAND SYSTEM	DIVISION SYSTEM
Type of crib	Permanent steel	Submerged
Diameter of tunnel system—feet	9	10, 7 and 5
Length of each sized tunnel—feet	26,000	16,100—9,200
Total cost of intake systems	$1,500,000	$2,530,000
Capacity of tunnel system—m. g. p. d.	175	175
Cost per million gallons per day of capacity	$8,550	$14,450
Average cost of cribs, tunnels, aqueducts and screen wells for Kirtland and Division systems per million gallons of daily capacity	$11,500	

Assumed life of cribs, tunnels, aqueducts and screen wells—100 years.

Cost of waterworks land. The cost of land used for waterworks purposes has not been included in this comparison as the yearly appreciation of Cleveland waterworks land more than covers the yearly cost of the bonds which are required for its purchase.

Pumping station costs

	KIRTLAND	DIVISION
Buildings (pumping engine and boiler house)	$600,000	$405,000
Triple expansion pumping engines	786,000	805,000
Boilers, piping and miscellaneous equipment	224,000	190,000
Total pumping station cost	$1,600,000	$1,404,000
Ultimate capacity of pumping stations—m. g. p. d.	165	165
Cost per million gallons of capacity	$9,700	$8,500
Average cost of both stations per million gallons of capacity	$9,100	

Assumed life of complete pumping stations—30 years

Filtration plant

Cost of Division Avenue filtration plant having a rated capacity of 150,000,000 gallons per day	$2,250,000
Cost per million gallons of capacity	$15,000
Assumed life of filtration plant	50 years
Cost of low-lift building, pumps and proportional cost of boilers and miscellaneous equipment	$297,000
Cost per million gallons capacity	$1,800
Assumed life of complete low-lift pumping station	30 years

Distribution system cost. We have assumed that the cost of the distribution system would be the same for direct as for reservoir pumpage, and have not included its cost in any data compiled herein.

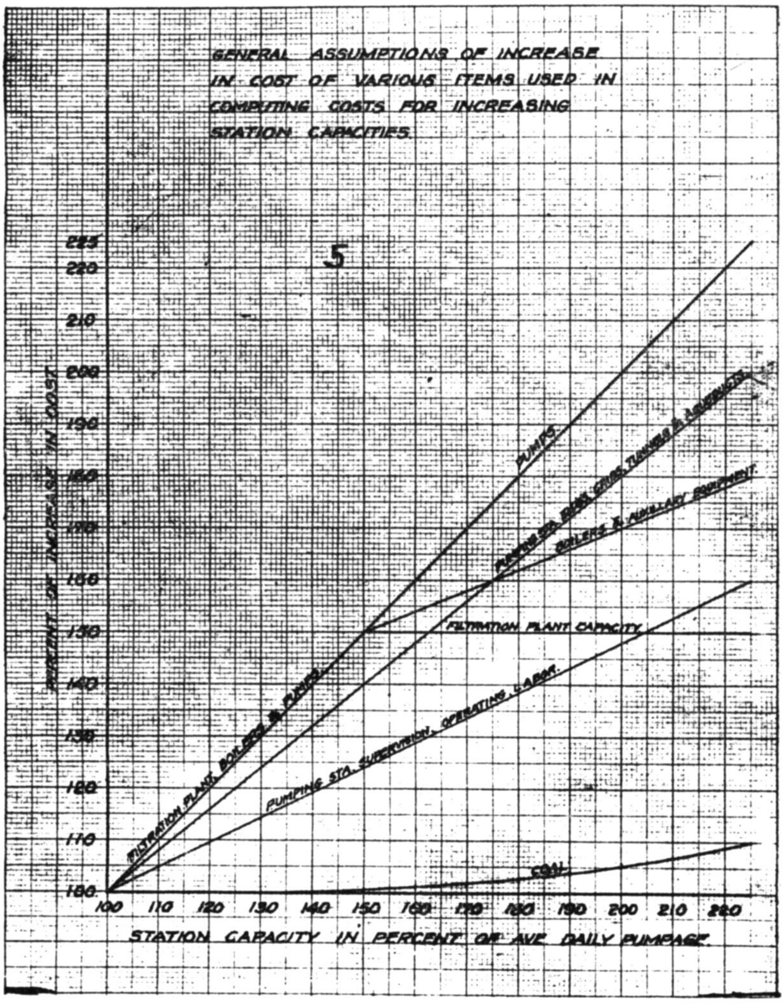
Reservoir costs

	FAIRMOUNT	KINSMAN	WARRENSVILLE
Capacity of reservoirs—gallons	80,500,000	35,600,000	22,300,000
Year completed	1885	1885	1914
Cost of reservoir	$404,400	$159,400	$137,600
Cost per million gallons	$5,300	$4,475	$6,170
Average cost of three reservoirs per million gallons of capacity	$5,315		

Assumed life of reservoirs—100 years

In determining the capital, operation, and maintenance costs of the tunnel systems, pumping stations, filtration plants and res-

ervoirs of proper capacity to take care of an average yearly demand of 100,000,000 gallons per day with pumping stations of various maximum capacities, a large number of assumptions had to be made



CURVE 5

and those having the greatest influence on this subject are shown diagrammatically in curve 5.

You will note from the curve labeled "Pumping Station Buildings, Cribs, Tunnels and Aqueducts" that we have increased the cost

80 per cent for double the capacity. This is due to the fact that the unit costs of the tunnel systems and pumping stations would be somewhat less for the larger capacities, and the boiler house building would be relatively smaller due to the fact that the boilers could be run at higher ratings for short periods and the tunnel size could be relatively smaller for peak demands than for steady demands, as the friction loss could be somewhat greater for a peak demand of a given rate than for a steady demand of the same rate. The tunnel capacity does not exceed 150,000,000 gallons per day when used in connection with a filter plant, as the clear water basin is assumed to take care of the hourly fluctuations of filtered water pumpage.

The pumping station, boiler and miscellaneous equipment costs curve shows that the costs vary directly with the station capacity up to 150,000,000 gallons per day and that they increase 30 per cent more for a 225,000,000 gallon capacity station as compared with the 150,000,000 gallon station.

You will note from the curve that the filter plant capacity does not exceed 150,000,000 gallons as the clear water basin is assumed to take care of all hourly fluctuations throughout a maximum demand day.

We have made no increase in the cost of coal for the plants operating up to 130 per cent capacity, but have assumed that the coal cost would be gradually increased until it becomes 10 per cent higher for direct pumpage at a 225,000,000 gallon peak than for a station which would only have to pump a maximum of 130,000,000 gallons per day.

With the direct system of pumpage, pumps and boilers run at a lower load factor, as the station must be ready at all times for large fluctuations in demands which would result in a somewhat lower over-all station duty and resulting increase in coal consumption.

The pumping station supervision and operation is assumed to increase 60 per cent for an increase in pumping station capacity of 125 per cent. The cost of tunnel operation, which includes cribkeeper's salaries, etc., remains the same irrespective of the size of the tunnel.

The open reservoir unit costs have been assumed to vary from $5500 per million gallons for a 10,000,000 gallon reservoir to $5000 per million gallons for a 200,000,000 gallon reservoir. The cost of the covered reservoirs is assumed to be double that of the open reservoirs.

Reservoir operation costs consisting principally of keeper's and gardener's salaries vary from $115 per million gallons for a 10,000,000 gallon reservoir to $15 for a reservoir of 200,000,000 gallons capacity or over.

Filter plant supervision, labor, chemicals and supplies are assumed to be the same over a year's period, whether the plant operates steadily at a 100,000,000 gallon rate or filters up to rates of 150,000,000 gallons per day, although with a plant taking care of a varying demand the chemical costs, for instance, might be slightly higher.

By the use of curves 4 and 5 and the tabulated costs of the pumping stations, tunnel systems, etc., given above, we have determined the combined first cost of various sizes of tunnels, pumping stations, filter plants and reservoirs required to take care of all variations in demand throughout the year. These costs are shown graphically on diagram 6.

Curve A represents the conditions of operation for Kirtland Pumping Station from its completion in 1904 to the present time.

Curve B represents the conditions of operation of the new Division Avenue Pumping Station and filter plant since its completion in 1917 to the present time.

Curve C would represent the conditions at Kirtland if it were a centrifugally equipped pumping station, after Baldwin reservoir is completed.

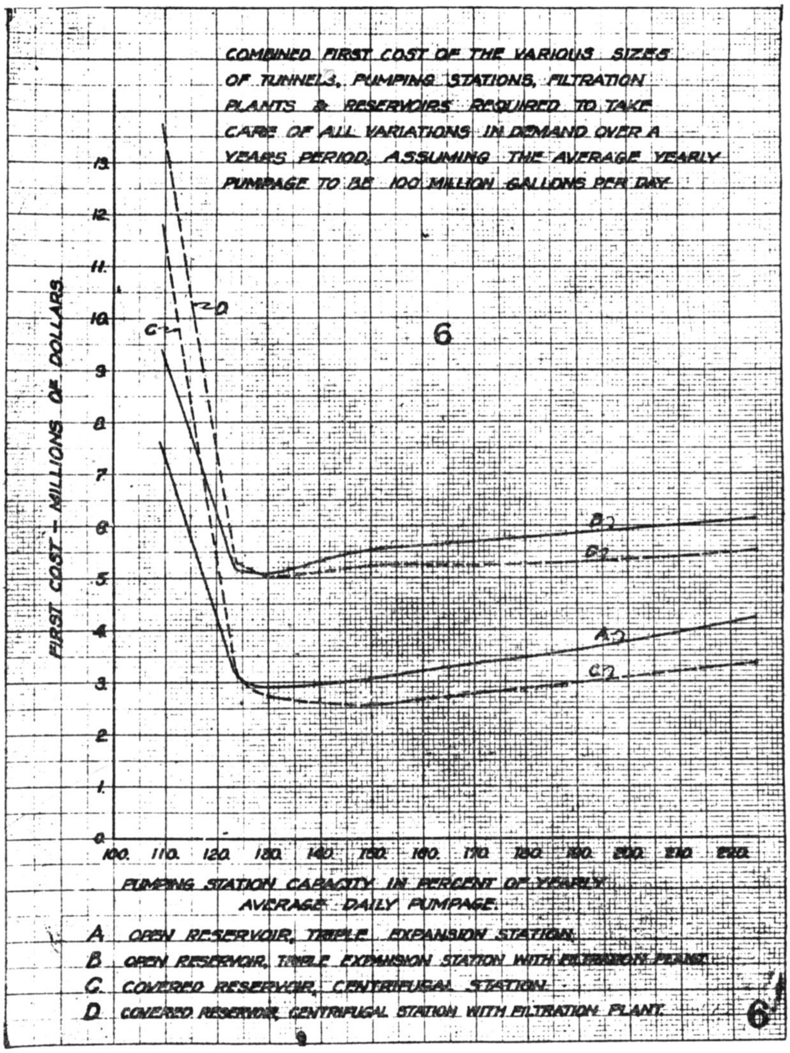
Curve D would represent the conditions of operation of Kirtland and Division pumping stations if they were equipped with centrifugal pumps and after Baldwin reservoir and filtration plant are completed.

The present tendencies point to a gradual change in many localities from triple expansion pumping stations and open reservoirs, to steam turbine driven centrifugal pumping stations and covered reservoirs, and curves A, B, C, and D, show the comparative costs of these different types of construction.

The capital charges for conditions A, B, and D, are all approximately a minimum for a 130,000,000 gallon capacity pumping station and a 60,000,000 gallon capacity reservoir, and for the centrifugal station, filter plant and covered reservoir combination of curve D, the minimum cost would be for a 150,000,000 gallon capacity pumping station and a 20,600,000 gallon reservoir.

These curves also show that it would be just as economical from the standpoint of first cost to either build pumping stations of

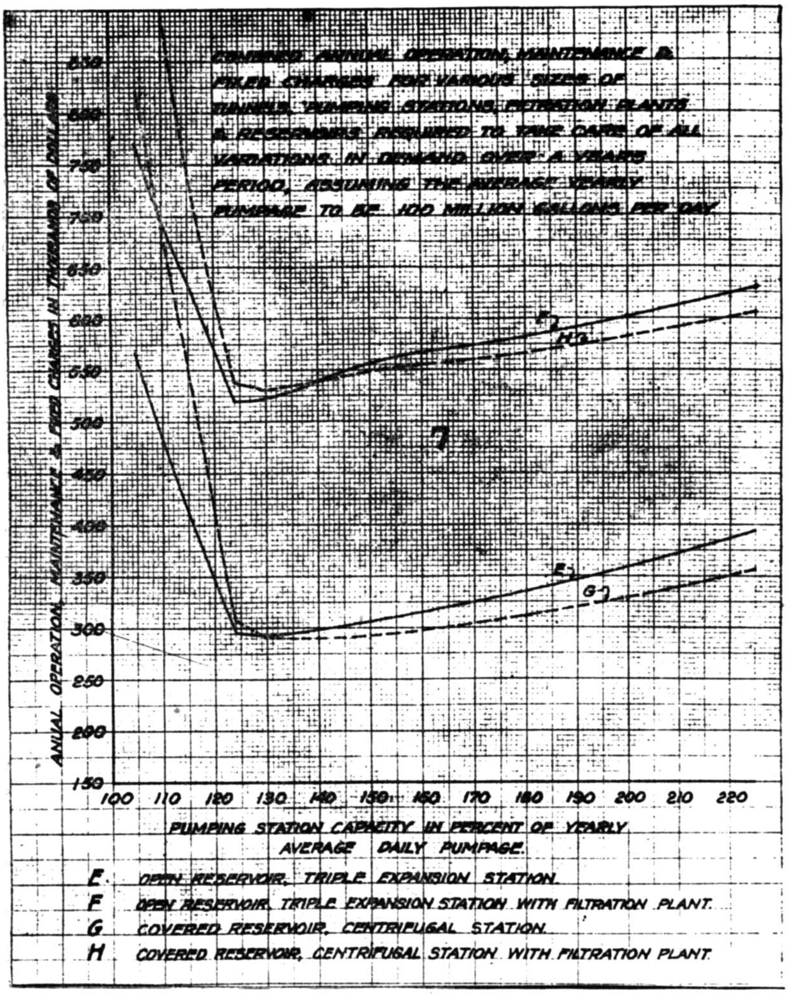
225,000,000 gallons capacity for direct pumpage or open reservoirs of approximately 340 million gallons capacity for conditions A and



Curve 6

B. and closed reservoirs of approximately 240,000,000 gallons capacity for conditions C and D with the corresponding sizes of pumping stations.

In the construction or reconstruction of a waterworks, the first cost is of relatively less importance than the annual costs made up of operation, maintenance and fixed charges.



CURVE 7

By the use of curves 4 and 5 and the assumptions given below, we have drawn curves E, F, G, and H, diagram 7, to show the combined annual operation, maintenance and fixed charges for various

sizes of tunnels, pumping stations, filtration plants and reservoirs required to take care of all variations in demand over a year's period, assuming the average yearly pumpage to be 100,000,000 gallons per day.

In computing the annual fixed charges we have assumed the life of the various waterworks properties to be a certain number of years, and have added to the yearly maintenance cost the annual payment required to retire a serial bond in the amount of the cost of the property, the bond having the same life as the waterworks property being considered. In other words, the money borrowed to pay for the construction of the tunnels, pumping stations, filtration plants and reservoirs, will have been paid back by the time they have become obsolete or worn out.

In computing maintenance, we have determined from our records what per cent our maintenance costs have averaged over a long period of years, and have applied that percentage to the costs of the various waterworks properties.

The general method of varying the operating costs for the increasing sizes of tunnels, pumping stations, filtration plants, and reservoirs, has been indicated above in the description of curve 5.

You will note that curves E and G are a minimum for 130,000,000 and 140,000,000 gallons per day respectively, while curves F and H reach their minimum points at 124,000,000 and 130,000,000 gallons per day respectively. The difference between these points in both cases is due to the fact that the cost of operation and maintenance of the triple expansion station with an open reservoir is relatively greater than for the centrifugally operated station with a covered reservoir and therefore the pumping capacity of the triple expansion station would be smaller than the centrifugal for the same annual costs. It will also be observed for curves F and H, which include a filtration plant, that the difference in pumping station capacity is 6,000,000, whereas for curves E and G, which do not include a filtration plant, the difference in pumping station capacity is 10,000,000. This is explained by the fact that the annual cost of the filtration plant is a relatively large percent of the entire annual waterworks cost and therefore the difference in annual cost between the triple expansion open reservoir combination and the centrifugal covered reservoir combination is relatively less.

It is interesting to note that the annual operating costs would be the same for direct pumpage as for pumping station and reservoirs having capacities as follows:

		Gallons
Condition E	Pumping station capacity	116,300,000
	Reservoir capacity	570,000,000
Condition F	Pumping station capacity	115,400,000
	Reservoir capacity	625,000,000
Condition G	Pumping station capacity	122,000,000
	Reservoir capacity	220,000,000
Condition H	Pumping station capacity	120,800,000
	Reservoir capacity	295,000,000

We would like to add here, as a matter of interest, that we have plotted curves using entirely different assumptions than were used in the plotting of diagrams 5, 6 and 7, and the general characteristics of the first cost and annual cost curves corresponding to diagrams 6 and 7 were not materially changed, which would indicate that the curves submitted cover a rather broad field in a general way. We have not included the additional curves or a discussion of them, as we did not wish to burden this paper with the further data.

In order to simplify the problem as much as possible, we have not included in our costs the additional investment which would be required to provide a reserve capacity for either pumping stations or reservoirs. We find, however, that our disregarding this item does not appreciably affect the data contained herein.

It is evident that the reservoir of the most economical combination would be required to change its contents 60,000,000 gallons, and a reservoir which would change 60,000,000 gallons in capacity would presumably be one of at least 80,000,000 gallons in actual total capacity, so that a reasonable reserve would be available for emergencies at all times.

The cost of this additional capacity would be approximately the same as the cost of the necessary reserve pump capacity which would be required at the pumping station.

Few waterworks are planned without provisions being made for continuous growth at a greater or less rate. The doubling of a size of a pumping station originally designed for such an extension could be done quite economically. However, another basin could be added to a reservoir which had proper provision made for it in the original construction with equal facility, so that in the matter of providing for future growth the pumping station and reservoir are not greatly different.

In conclusion, we believe that a study of the curves and data discussed herein will give one a fair idea of the relative merits of reservoirs as compared with additional pumping capacity for taking care of the various fluctuations in demand that a waterworks system is called upon to meet. The inherent ease with which a reservoir can meet large and rapid fluctuations in demand, its great value as an emergency reserve, as well as its economy in annual cost, make possible its great value for waterworks service.

For conditions of demand similar to those discussed, the use of the direct system of pumpage would be a questionable economy even though reservoir sites were not available, as a study of the curves indicate that steel or concrete tower tanks of several times the unit costs of reservoirs, could be constructed to take care of hourly fluctuations with considerable resulting economy.